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TITLE: Exposure apparatus and method

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Abstract Text - ABTX (1):

A projection exposure method for exposing a substrate through a projection optical system with a predetermined pattern formed on a mask. The method includes the steps of calculating an amount of lateral variation of a pattern image in a direction perpendicular to an optical axis of the projection optical system, determining a distortion produced solely by the projection optical system, obtaining a total expected distortion by a summation of the distortion produced solely by the projection optical system and the calculated variation of the positions at which the image of the pattern of the mask is formed, and exposing the substrate while partially **correcting** the positions at which the image of the pattern of the mask is formed through the projection optical system based on the total expected distortion.

Brief Summary Text - BSTX (3):

In a photolithographic process for fabricating semiconductor devices or other products, there have been used various projection exposure apparatus including stepping projection exposure apparatus called stepping projection aligners or steppers, as well as scanning projection exposure apparatus called scanning projection aligners or step-and-scan projection aligners. These projection exposure apparatus use a projection optical system

(or projection lens) which has to provide an extremely high resolution approaching the theoretical resolution limit. In order to support such a high resolution, many projection optical systems have certain mechanisms for measuring various factors in the resolution (such as, the atmospheric pressure and the ambient temperature) and then **correcting** the image formation characteristics of the projection optical system depending on the result of such measurement. For higher resolution, projection optical systems are designed to have a large numerical aperture. As a result, the depth of focus is very small. Thus, many projection optical systems have a autofocus mechanism which may comprise an oblique-incidence focus position detection system (or AF sensor). The AF sensor serves to measure the focus position (or the position in the direction along the optical axis of the projection optical system) of the surface of a wafer (or substrate) which typically has some irregularities. The autofocus mechanism brings the surface of the wafer into a position at which it will be coincident with the image plane of the projection optical system, based on the result of such measurement.

Brief Summary Text - BSTX (4):

In recent years, image formation errors caused by **deformation** of a mask or reticle have become a problem. If substantially all the pattern-bearing surface area of a reticle is deformed down toward the projection optical system, the average position of the image plane (or image surface) of the pattern-bearing surface is displaced downward, so that the focus position of a wafer could suffer from defocusing if it were not adjusted. Further, when the pattern-bearing surface of a reticle is deformed, the

positions of the pattern,
which are perpendicular to the optical axis of the projection optical system,
on the pattern-bearing surface may also is displaced. Such lateral
displacements (or displacements in the direction perpendicular to the optical
axis of the projection optical system) may cause distortion errors.

Brief Summary Text - BSTX (6):

There have been many proposals to reduce lens aberrations contributed to by
factors involved in the fabrication process. One such technique uses one or
more aberration **correction** plates disposed between the projection optical
system and the wafer (or glass substrate), for canceling out the aberrations.
Specifically, any residual aberrations which remain after final adjustment of a
lens are canceled out by the reverse aberrations intentionally produced by the
aberration **correction** plates so as to minimize the resultant lens aberrations.
The residual aberrations may be determined by making and analyzing a test.
print using that lens together with a test reticle having evaluation patterns
formed thereon, or by measuring the position of aerial images of evaluation
patterns of a test reticle formed by that lens by means of a measuring
photodetector.

Brief Summary Text - BSTX (7):

There have been further factors affecting the final image formation
characteristics of a lens, which relate to the accuracy (or drawing errors) in
the evaluation patterns of a test reticle. In particular, the patterning
accuracy (including the linewidth accuracy) of a test reticle is of great
concern. In order to **correct** errors arising from insufficient patterning

accuracy, a system has been used in which the pattern positions (or the distances between the patterns) of a finished test reticle are measured and stored using a precision coordinate measurement device, and the positions of the projected images are **corrected** by an utilization of the stored pattern positions.

Brief Summary Text - BSTX (8):
As described above, when the image formation characteristics of a projection optical system are evaluated, measurement errors due to insufficient patterning accuracy of an evaluation reticle may be **corrected** by an utilization of the pattern positions which are measured and stored in advance. However, there are further structural factors affecting the final or total image formation characteristics of the projection exposure apparatus, including the flatness of the exposure area of an evaluation reticle, flatness of the area outside the exposure area of a reticle, and the deflection of a reticle when it is loaded on the projection exposure apparatus. In the past when requirements for the image formation characteristics were less severe, the need for various accuracies relating to these structural factors did not arise. However, in recent years, requirements for the patterning accuracy of semiconductor chips and the registration accuracy between **layers** of the semiconductor chips have become very severe, so that the accuracies relating to the above structural factors have become of more significance in order to meet such requirements.

Brief Summary Text - BSTX (11):
However, holding a mask on a mask holder in this manner suffers from a problem that the mask 900 is deflected by the gravity as

shown in FIG. 30(A).
This results in the lateral displacements of the features of the pattern formed on the mask 900 as well as the curve of the image surface defined by the projection optical system. Further, irradiation of the exposure light rays onto the mask 900 during exposure operations imparts irradiation heat to the mask 900 and increases its temperature, this results in the thermal expansion of the mask 900. Since the mask 900 is secured at its peripheral area onto the mask holder 902, the mask 900 is deformed as shown in FIG. 30(B). As the result, the pattern on the mask 900 is also deformed, which may disadvantageously produce variation In the distortion of the projected pattern image and/or add to the curvature of the image surface so that the depth of focus in the pattern-bearing surface of the mask become inconveniently smaller.
With today's highly miniaturized patterns, even a minute **deformation** of the pattern can be of great concern.

Brief Summary Text - BSTX (12):
Apart from deflection caused by gravity, the **deformation** of a mask or reticle may be also caused In the polishing process of the glass plate forming the reticle, or may be caused depending on insufficient flatness of one or both of the contact surfaces of the reticle and the reticle holder, which are forced to come into contact with each other by vacuum suction. Since there is difference in the deflections between reticles, or between projection exposure apparatus, a deflection of a particular reticle has to be measured when it is held on the reticle holder of a particular projection exposure apparatus in order to obtain an accurate reticle **deformation**.

Brief Summary Text - BSTX (13):
One method for measuring the **deformation** of the pattern-bearing surface of a reticle held on the reticle holder of a projection exposure apparatus by vacuum suction may comprise the steps of making and analyzing a test print using the projection optical system of that projection exposure apparatus. The selected features of the pattern formed on the pattern-bearing surface of the reticle are projected through the projection optical system onto a wafer for evaluation. This projection exposure is repeated while the focus position of the wafer is varied in a stepwise manner. After the development process of the resist **layer** on the wafer, the resist patterns thus formed are examined for their contrast, and the exposure specifications for the resist patterns of the highest contrast among those corresponding to the same features of the reticle pattern indicate the best-focus positions of the projected images of the respective features of the reticle pattern. Then, from the displacements of the best-focus positions, the **deformation** of the pattern-bearing surface of the reticle may be calculated quantitatively to a certain extent.

Brief Summary Text - BSTX (16):
In particular, for a scanning projection exposure apparatus, since the reticle stage used therein has to show sufficient rigidity to prevent any harmful **deformation** when accelerated/decelerated for movement in synchronism with the wafer stage for scanning, the reticle stage is generally given a sufficient thickness, thereby usually the bottom surface of the reticle is close to the upper end of the projection optical system. Further, the smaller the space distance between the reticle and the projection optical system, the easier the projection optical system may be designed, so that

projection optical systems having a greater precision tend to provide less space between the reticle and the projection optical system. Thus, it is difficult to dispose a position sensor for measuring the surface shape of a reticle in the space between the projection optical system and the reticle.

Brief Summary Text - BSTX (17):
Moreover, a position sensor for measuring the surface shape of a reticle must have a high stability against aging. This is because even such a variation in measurements provided from the position sensor, that is actually caused by aging, is interpreted as indicating a variation in the surface shape of the reticle, leading to an erroneous **correction** of the image formation characteristics.

Brief Summary Text - BSTX (21):
In the case where the reticle support portions 943 for supporting the reticle R thereon are formed as vacuum chucks, the deflection of the reticle R by the gravity may be suppressed by the **corrective** forces acting from the top surfaces of the reticle support portions 943, when the top surfaces are level or extend horizontally. However, since the recent years' projection lenses have a very high numerical aperture with a extremely small depth of focus, and there is the need for the improvement of the overlay accuracy in order to support the more and more reducing linewidth, even a relatively low level of residual deformations of reticles after the **correction by the corrective** forces by vacuum chucks may arise a problem.

Brief Summary Text - BSTX (22):
As regards the reticles used for exposure of silicon

wafers, 5-in. square reticles are being replaced by 6-in. square reticles. Simultaneously, reticles of 0.09-in. in thickness are being replaced by those of 0.25-in. in thickness for the purpose of reducing any errors which may occur due to the **deformation** of reticles. In view of recent trends in the semiconductor device industry, greater exposure fields and greater reticle sizes are expected to be required and become common in the near future. The expected next generation of reticles are 9-in. square reticles, for which the thickness of about 0.5 in. would be required in order to meet both a focus condition of .+-.0.1 mm and a distortion tolerance or 0.005 mm. It is expected that 9-in. square reticles would become common in 2000 A.D., where scanning projection exposure machines in which a reticle and a wafer are moved in synchronism with each other would be the prevailing exposure machines. A reticle of a greater thickness means a heavier reticle, which may arise a problem regarding the secure holding of a reticle by the reticle holder since a reticle must be accelerated and decelerated for scanning projection exposure. Further, for enhancing the throughput, high speed operations of exposure machines are required, which would lead to a limitation on the weight of a reticle. Thus, the thickness of a reticle should be a compromise between the anti-deflection and throughput requirements, which may not be ideal in view of the anti-deflection capability. Accordingly, it is difficult to meet both the desired focus condition and distortion tolerance with any of conventional techniques.

Brief Summary Text - BSTX (27):

The fourth object of the present invention is to provide projection exposure apparatus and method with which the thickness and weight of a

reticle may be
suppressed and any pattern transfer errors due to the
deformation of the
reticle may be eliminated.

Brief Summary Text - BSTX (28):

In order to achieve the above-mentioned first object, in accordance with the present invention, there is provided a projection exposure apparatus for projecting an image of a pattern formed on a mask onto an object of exposure, comprising: a deflection detection device for detecting deflection of the mask; a deflection **correction** device for **correcting** deflection of the mask; an arithmetic device for calculating a deflection **correction** value for the deflection **correction** device based on the detection result obtained by the deflection detection device; and a control device for controlling the deflection **correction** device in accordance with the deflection **correction** value calculated by the arithmetic device.

Brief Summary Text - BSTX (29):

In several embodiments of significance, the deflection detection device comprises: a light-beam-projecting device for obliquely projecting a light beam onto the mask; and a light-beam-detecting device for detecting a reflected light beam projected by the light-beam-projecting device and reflected by the mask so as to produce a detection signal corresponding to the variation in the position at which the reflected light beam is received. Further, the deflection **correction** device may **correct** deflection of the mask by changing pneumatic pressure, or alternatively, the deflection **correction** device may **correct** deflection of the mask by operating a piezoelectric actuator element.

Brief Summary Text - BSTX (30):
In accordance with this aspect of the present invention, any deflection of the mask produced by the gravity and/or the thermal expansion is detected by, for example, an oblique-incidence detection system. Based on the detection result, a deflection **correction** value is calculated and the deflection is **corrected**. As the result, any curvature of the pattern image is suppressed and an accurate and stable image of the mask pattern may be obtained. In several embodiments of significance, the deflection of the mask is **corrected** and any variation in the projected image is **corrected** by changing pneumatic pressure or operating a piezoelectric actuator element.

Brief Summary Text - BSTX (31):
In order to achieve the above-mentioned second object, in accordance with the present invention, there is provided a projection exposure method for making a projection exposure of an image of a pattern formed on a mask through a projection optical system onto a substrate, comprising the steps of: measuring and. storing a surface shape of a pattern-bearing surface of the mask; and making an exposure while partially **correcting,** based on the surface shape as stored, the position at which an image of the pattern of the mask is formed through the projection optical system.

Brief Summary Text - BSTX (32):
With this projection exposure method, for example, a **correction** mechanism may be used for **correcting** image formation characteristics including the distortion by driving one or some of the lens elements of the projection

optical system. Further, for example, by using a distortion evaluation mask having evaluation patterns formed thereon, the positions of projected images of the evaluation patterns are measured so as to determine the distortion actually produced by the projection optical system. However, the determined distortion contains error components due to lateral displacements of features of the pattern on the pattern-bearing surface produced by the **deformation** of the surface shape thereof. Therefore, from the measured surface shape of the pattern-bearing surface of the distortion evaluation mask, a distribution of expected displacements of projected images of the evaluation patterns from their desired projection positions is calculated. Then, the measurements of the distortion is adjusted with the expected displacements so as to derive a distortion to be produced solely by the projection optical system. In the actual exposure process, the surface shape of the mask for the actual exposure process is measured, and the measurement result is used to calculate the expected lateral displacements of the points in the projected image which are expected to be produced by the surface shape. Then, the expected displacement of the projected image is added to the distortion which is produced solely by the projection optical system so as to derive a total expected distortion. The **correction** mechanism **corrects** the total expected distortion, so that excellent image formation characteristics may be obtained even when the mask has irregularities in its surface or suffers from tilt.

Brief Summary Text - BSTX (33):
This projection exposure method may be also applied to projection exposure apparatus of the type called step-and-scan projection aligners, in which the

surface shape of a mask may possibly vary depending on the position on the mask in the scanning direction, so that the distortion **correction** value has to be varied while the mask is moved for scanning. In such a case, the **correction** mechanism may control the distortion **correction** value depending on the position of the mask during an scanning projection exposure operation, so that excellent image formation characteristics may be obtained over the entire region in the scanning direction. Further, in such a case, if the distortion of the projection optical system has been well **corrected,** the distortion **correction** may be performed such that only the lateral displacements of the points in the projected image which are produced by the surface shape of the pattern-bearing surface of the mask may be canceled out.

Brief Summary Text - BSTX (34):
In order to achieve the above-mentioned second object, in accordance with the present invention, there is also provided another projection exposure method for making a projection exposure of an image of a pattern formed on a mask through a projection optical system onto a substrate, the mask being supported by a predetermined support member, comprising the steps of: measuring and storing any irregularities (including tilt) in a contact surface of the mask in contact with the support member; and making an exposure while partially **correcting,** based on the irregularities in the contact surface as stored, the position at which an image of the pattern of the mask is formed through the projection optical system.

Brief Summary Text - BSTX (35):
With this projection exposure method, the mask may be

secured onto the support member by vacuum suction. In such a case, if the contact surfaces (245A to 245D) of the mask which are in contact with the support member are tilted as shown in FIG. 17(B), the mask is caused to curve as shown in FIG. 17(C) when it is secured by the vacuum suction, so that the flatness of the mask is deteriorated. This problem may be solved by: determining, based on any irregularities in the contact surfaces between the mask and the support member, an expected variation in the irregularities in the contact surface of the mask which is expected to be produced when the mask is secured onto the support member by vacuum suction; adjusting the measurement result of the distortion of the projection optical system by the expected lateral displacement of the projected image; and **correcting** the image formation characteristics based on the adjusted distortion, so that excellent image formation characteristics may be obtained.

Brief Summary Text - BSTX (36):

In order to achieve the above-mentioned second object, in accordance with the present invention, there is also provided further another projection exposure method for making a projection exposure of an image of a pattern formed on a mask through a projection optical system onto a substrate, the mask being supported by a predetermined support member, comprising the steps of: measuring and storing any irregularities (including tilt) in a contact surface of the support member in contact with the mask; and making an exposure while partially **correcting,** based on the irregularities in the contact surface as stored, the position at which an image of the pattern of the mask is formed through the projection optical system. With this projection

exposure method,
if the contact surfaces of the support member in contact with the mask are
tilted, the mask is caused to curve as shown in FIG. 17(A) when it is secured
by the vacuum suction onto the contact surfaces. This problem may be solved
by: determining an expected variation in the irregularities in the surface of
the mask which is expected to be produced when the mask is secured onto the
support member by vacuum suction; and **correcting** the measurements of the
distortion of the projection optical system based on the expected variation
thus determined, so that excellent image formation characteristics may be
obtained.

Brief Summary Text - BSTX (37):
In order to achieve the above-mentioned second object, in accordance with
the present invention, there is also provided a projection exposure apparatus
for making a projection exposure of an image of a pattern formed on a mask
through a projection optical system onto a substrate, comprising: a measurement
system for measuring a surface shape of a pattern-bearing surface of the mask:
a storage for storing data representing the surface shape measured by the
measurement system; an image formation characteristics **correction** system for
partially **correcting** the position at which an image of the pattern of the mask
is formed through the projection optical system: and a control system for
making an exposure while **correcting,** through the image formation
characteristics **correction** system and based on the data in the storage
representing the surface shape, the position at which an image of the pattern
of the mask is formed through the projection optical system. With this
projection exposure apparatus, the projection exposure

methods described above
for achieving the above-mentioned second object may be conveniently performed.

Brief Summary Text - BSTX (38):
In order to achieve the above-mentioned third object, in accordance with the present invention, there is provided a scanning projection exposure method in which a mask and a substrate are moved in synchronism with each other for transferring a pattern formed on the mask through a projection optical system onto the substrate, comprising the steps of: measuring a surface shape of a pattern-bearing surface of the mask, prior to making a scanning projection exposure of the substrate with the pattern of the mask; and **correcting** at least one of 1) image formation characteristics of the projection optical system and 2) the position of the substrate, based on the measurement result of the pattern-bearing surface, while making a scanning projection exposure.

Brief Summary Text - BSTX (39):
With this scanning projection exposure method, the surface shape of the pattern-bearing surface of the mask can be measured while at least a part of the pattern-bearing surface is in an area outside a transfer area to be transferred by the projection optical system, so that the sensor for measuring the surface shape of the mask may be disposed at a position away from the projection optical system to the scanning direction. Accordingly, the sensor may be disposed with ease even when there is little space between the projection optical system and the mask stage and be used to measure the **deformation** (or the deflection) of the mask. Either the image formation characteristics of the projection optical system or the

position of the
substrate may be **corrected** based on the measured **deformation,**
so that excellent
image formation characteristics may be obtained.

Brief Summary Text - BSTX (40):
With this method, it is preferable to perform the measurement of a surface shape of the pattern-bearing surface of the mask while the mask stands still at a starting point for scanning or while the mask is being accelerated for scanning. That is, when a mask replacement is done, by measuring a surface shape of the pattern-bearing surface of the new mask once while the pattern-bearing surface of the new mask is at a starting point for scanning or in an acceleration region, the necessary **correction** may be made during the subsequent exposure operation. Further, in the case where the surface shape measurement is performed in the acceleration region, it is unnecessary to extend the stroke of the movement of the mask for the surface shape measurement. Moreover, the measurement of a surface shape of the mask may be alternatively performed while the mask is being scanned for exposure, while the mask is being decelerated after scanning, or while the mask stands still after deceleration.

Brief Summary Text - BSTX (41):
In order to achieve the above-mentioned third object, in accordance with the present invention, there is also provided a scanning projection exposure apparatus in which a mask and a substrate are moved in synchronism with each other for transferring a pattern formed on the mask through a projection optical system onto the substrate, comprising: a shape measurement system defining a plurality of detection points in an area outside a

transfer area to
be transferred by the projection optical system, for measuring a surface shape
of a pattern-bearing surface of the mask; and a **correction** system for
correcting at least one of 1) image formation characteristics of the projection
optical system and 2) the position of the substrate, based on the measurement
result by the shape measurement system.

Brief Summary Text - BSTX (43):
It is preferable to form a reference surface on a mask stage for moving the
mask, such that the reference surface may be substantially level with the
pattern-bearing surface of the mask. In such a case, at first the measurement
by the shape measurement system is performed by measuring the position of the
reference surface, and then measuring the surface position of the reticle with
reference to the measured position of the reference surface. That is, the
differential between the reference surface and the surface position of the mask
is measured. By virtue of this, it is sufficient for the shape measurement
system to have such stability for a very short time from when the reference
surface has been measured to when the surface of the mask has been measured.
Thus, even if the measurements produced from the shape measurement system tend
to fluctuate within a certain period, the expected variation in the image
formation characteristics may be determined with precision so as to make an
appropriate **correction** for the variation.

Brief Summary Text - BSTX (45):
In order to achieve the above-mentioned fourth object, in accordance with
the present invention, there is provided a projection exposure apparatus,
comprising: a first holder for holding a master matrix; an

illumination optical
system for illuminating the master matrix; a projection optical system for
focusing light rays which pass through the master matrix on a photosensitized
substrate so as to form an image thereon; and a second holder for holding the
photosensitized substrate; wherein error factors due to the **deformation** of the
master matrix produced by the gravity when the master matrix is held on the
first holder have been **corrected** through a design process of a projection lens.

Brief Summary Text - BSTX (46):
In stead of, or in addition to, the **correction** of the errors through the
design process of the lens, an adjustment mechanism for the projection lens may
be used to **correct** the errors in an adjustment process for the apparatus.

Brief Summary Text - BSTX (47):
In order to achieve the above-mentioned fourth object, in accordance with
the present invention, there is also provided a projection exposure method for
making a projection exposure of a pattern on a master matrix onto a
photosensitized substrate to transfer the pattern onto the substrate,
comprising the step of**: correcting,** through a design process of a projection
lens, error factors due to the **deformation** of the master matrix produced by the
gravity when the master matrix is held.

Brief Summary Text - BSTX (48):
That is, any focus errors and distortion errors which are expected to be
produced by the deflection of a reticle are **corrected** through a reticle design
process or an adjustment process. Therefore, any pattern transfer errors due

to the **deformation** of a reticle may be eliminated even when the reticle has a relatively small thickness.

Brief Summary Text - BSTX (49):
With this projection exposure method, it is preferable to determine errors due to the **deformation** of the master matrix produced by the gravity, through an exposure process or a measurement process performed using a reference master matrix, and adjust a projection lens of the projection optical system such that the errors may be eliminated, and then make an actual exposure. In this case, any errors are determined and **corrected** through the adjustment process, so that even the error produced by the reticle chucks may be determined and **corrected**.

Drawing Description Text - DRTX (23):
FIG. 21 is a schematic side elevation illustrating the **deformation** of the image surface due to the **deformation** of the pattern-bearing surface of a reticle;

Drawing Description Text - DRTX (26):
FIG. 24 is a flow chart illustrating an exemplified sequence of operations for performing exposure process while **correcting** the image formation characteristics according to a further embodiment of the present invention for achieving the above-mentioned third object;

Detailed Description Text - DETX (7):
Referring again to FIG. 1, the output of the arithmetic operation unit 32 is coupled to a pneumatic-pressure control unit 34, which is in communication with a mask-deflection **correction** unit 38 through a conduit pipe 36. The

mask-deflection **correction** unit 38 comprises a box having side walls with their lower edges capable of airtight abutment with the mask 10 and a top wall made from a highly plane, highly clear glass plate not affecting the exposure light beam. Thus, the box together with the mask 10 defines an air chamber 40. The pneumatic pressure within the air chamber 40 may be controlled by the pneumatic-pressure control unit 34 in order to control any deflection of the mask 10. The pneumatic-pressure control unit 34 is capable of controlling the pneumatic pressure within the air chamber 40 depending on the desired pneumatic-pressure control value supplied from the arithmetic operation unit 32.

Detailed Description Text - DETX (9):

When the mask 10 is deformed, and thus changes its shape from that shown by solid lines to that shown by broken lines in FIG. 2(B) or 2(C), then the path of the light beam from the light source 24 will be changed from that shown by solid lines to that shown by broken lines. The mask 10 is deformed downward and upward in FIGS. 2(B) and 2(C), respectively. The detection signals from the photodetector 30 produced when the position of the incident point of the light beam on the sensitive surface of the photodetector 30 varies are supplied to the arithmetic operation unit 32. The arithmetic operation unit 32 performs comparison of the supplied detection signals with the detection signals representing the reference position as shown in FIG. 2(A), and uses the comparison to derive the magnitude of the deflection of the mask 10 or the displacement of a particular position on the mask 10 from the reference position mentioned above. The arithmetic operation unit 32 further calculates

the desired pneumatic-pressure control value which is required for **correcting**
the detected deflection of the mask 10.

Detailed Description Text - DETX (10):

The desired pneumatic-pressure control value is supplied to the pneumatic-pressure control unit 34, which controls the pneumatic pressure within the air chamber 40 of the mask-deflection **correction** unit 38 so as to **correct** the detected deflection of the mask 10. The **correction** of the deflection of the mask 10 may be performed in this manner either continuously or periodically at. an appropriate frequency so that any deflection of the mask 10 due to the gravity and/or possible thermal expansions may be **corrected**.

Detailed Description Text - DETX (11):

As clearly understood from the above, according to the first embodiment, any deflection of the mask 10 is detected by the mask-deflection detection system 22, the magnitude of the deflection as well as the desired pneumatic-pressure control value for **correcting** the deflection are calculated by the arithmetic operation unit 32, and the pneumatic pressure within the air chamber 40 of the mask-deflection **correction** unit 38 is controlled by the pneumatic-pressure control unit 34. In this manner, any lateral displacements of the images of the features of a pattern and curvature of field both of which may result from the deflection of the mask 10 due to the gravity, or any distortion and curvature of field due to the thermal **deformation** of the mask 10, may be reduced and thereby the projection of the mask pattern may be appropriately performed.

Detailed Description Text - DETX (12):
Referring next to FIG. 3, the second embodiment will be described in detail.
In FIG. 3, like elements are designated by like reference numerals as used for the elements of the first embodiment. While the first embodiment utilizes an air chamber for the purpose of **correcting** the deflection of the mask, the second embodiment utilizes a set of piezoelectric actuator elements for the same purpose. FIG. 3(A) shows a critical portion of the second embodiment, and FIG. 3(B) shows the plan view of a mask. As shown in these figures, a set of piezoelectric actuator elements 50A to 50H are disposed on the top surface of the mask 10 along its peripheral edges. The piezoelectric actuator elements 50A to 50H are mounted onto a fixed frame 52 surrounding the mask 10 and comprising four side members having an L-shaped cross-section. The mask is held at a plurality of points on its under side along its peripheral edges onto corresponding platens 54A to 54H by vacuum suction. The fixed frame 52 is fixedly mounted onto the mask holder 54.

Detailed Description Text - DETX (14):
The second embodiment comprises a mask-deflection detection system 22 having the same arrangement as that used in the first embodiment described above. The output of the photodetector 30 is coupled to an arithmetic operation unit 58, the output of which is in turn coupled to a voltage control unit 58. The output of the voltage control unit 58 is coupled to the set of piezoelectric actuator elements 50A to 50H through the fixed frame 52. The arithmetic operation unit 56 is capable of calculating the magnitude of the deflection of the mask 10 based on the detection signals supplied from the photodetector 30

as well as calculating the desired voltage control value indicating the voltage which has to be applied to the piezoelectric actuator elements 50A to 50H for **correcting** the detected deflection of the mask 10. The voltage control unit 58 is capable of controlling the voltage to be applied to the piezoelectric actuator elements 50A to 50H in accordance with the desired voltage control values supplied thereto.

Detailed Description Text - DETX (16):

FIG. 3(C) shows a cross-sectional side view of the mask 10 along line C3--C3 of FIG. 3(B). The mask 10 generally tends to deflect downward as indicated by solid lines in FIG. 2(B). In the second embodiment, the platens 54C and 54H are disposed inside to the piezoelectric actuator elements 50C and 50H as shown in FIG. 3(C). Therefore, if the piezoelectric actuator elements 50C and 50H are applied with a voltage having such polarity that cause them to elongate in the vertical direction, the right and left ends (as viewed in FIG. 3(C)) of the mask 10 is deflected downward as indicated by arrows FA. Since the platens 54C and 54H serves as the fulcra, the central portion of the mask 10 is deflected upward as indicated by arrow FB. By virtue of this, the downward deflection of the mask 10 may be **corrected**. This control of the piezoelectric actuator elements 50C and 50H is done by the voltage control unit 58. The other piezoelectric actuator elements are controlled in the same manner.

Detailed Description Text - DETX (17):

As clearly understood from the above, according to the second embodiment, any deflection of the mask 10 is detected by the mask-deflection detection system 22, the magnitude of the deflection as well as the

desired voltage control values for **correcting** the deflection are calculated by the arithmetic operation unit 56, and the voltages to be applied to the piezoelectric actuator elements 50A-50H are controlled by the voltage control unit 58. In this manner, this embodiment may achieve the same advantages as the first embodiment described above.

Detailed Description Text - DETX (19):

A projection optical system 106 is disposed on the beam-exiting side of the mask 102. FIG. 5 shows an exploded perspective view of a critical portion of the projection optical system 106. As seen, the projection optical system 106 comprises first and second lens element 108 and 110 between which three piezoelectric actuator elements 112A-112C are disposed along their peripheral edges. The piezoelectric actuator elements 112A-112C may elongate/shorten to control the distance between the lens elements 108 and 110. In addition, since three piezoelectric actuator elements 112A-112C are used to support the first lens element 108, it may be tilted with respect to a plane perpendicular to the optical axis of the projection optical system 106. These distance and tilt adjustments enable the **correction** of any variations in the projected image which may be caused by possible deflection of the mask 102, such as any variations in magnification and any distortions due to the deflection.

Detailed Description Text - DETX (22):

During this scanning projection operation, if the mask 102 is deflected, the deflection is detected by the mask-deflection detection system 22 as with the above-described embodiments, and the magnitude of the deflection is calculated

by the arithmetic operation unit 104. The arithmetic operation unit 104 further uses the calculation results to derive the expected adverse effects of the deflection of the mask 102 on the projected image, and calculates the voltage control values indicating the respective voltages to be applied to the piezoelectric actuator elements 112A-112C in order to **correct** the expected adverse effects on the projected image. The voltage control values are supplied to the voltage control unit 118, so that the voltages applied to the piezoelectric actuator elements 112A-112C in the projection optical system 106 are controlled. In this manner, the lens element control of the projection optical system 106 is performed such that the relationship between the lens elements 108 and 110 is adjusted so as to **correct** any adverse effects of the mask-deflection on the projected image.

Detailed Description Text - DETX (24):

The mask 172 may be deflected in the Z-direction as indicated by arrows FQ and FR due to some causes such as the gravity. It may be ideal that the deflection of the mask 102 is **corrected** with respect to both of the X- and Y-directions corresponding to arrows FQ and FR. Nevertheless, the light beam 170 has an elongate cross section which produces an elongate light spot on the mask. 172 which is short in the scanning direction (or the X-direction) and wide In the lateral direction (or the Y-direction). In view of such particular shape of the light spot produced by the light beam 170, it is more practical for the pattern projection purposes that the deflection along the X-direction as indicated by arrow FQ is **corrected** by focusing and/or levelling operations, and only the deflection along the Y-direction as indicated by arrow FR is

eliminated.

Detailed Description Text - DETX (25):
Thus, in this embodiment, a set of piezoelectric actuator elements 174A-174F are disposed such that the deflection of the mask 172 along the Y-direction as indicated by arrow. FR may be eliminated thereby, or the positions along a pair of edges of the mask 172 extending in the moving direction of the light beam 170. The deflection of the mask 172 is detected and **corrected** in the same manner as with the second embodiment described above. For example, when the light beam 170 falls on the mask 170 at the position near two of the piezoelectric actuator elements, 174C and 174D, the deflection may be **corrected** by activating them. In this manner, the mask 172 may be caused to produce a **corrective,** counteractive deflection as indicated by arrow FS, which may cancel out the original deflection as indicated by arrow FR.

Detailed Description Text - DETX (26):
Various modifications and alterations may be made to the embodiments described above, and are apparent to those skilled in the art having read the above disclosure. Such modifications and alterations include the followings.
(1) While the first embodiment utilizes a pneumatic pressure for the purpose of **correcting** the deflection of the mask, it is also possible to use a hydraulic pressure. However, to use a pneumatic pressure is preferable in view of the handling of a mask and the prevention of leakage of a liquid. (2) While each of the embodiments described above detects the deflection of the mask at a single point on the mask, they may be modified such that the deflection is detected at a plurality of points on the mask and an optimal **correction** for the

deflection may be calculated by.using an appropriate arithmetic operation such as averaging and/or least-squares method. In order to detect the deflection at a plurality of points on the mask, a plurality of mask-deflection detection systems, each corresponding to that shown above, may be used. Alternatively, a diffraction grating may be used to produce a plurality of light beams from a single light beam output from a single light source, which enables simplification of the arrangement. (3) With each of the second, third and fourth embodiments described above, a magnitude of the deflection of the mask may be detected at each of a plurality of points on the mask and a voltage control value may be derived for each of the piezoelectric actuator elements individually. This enables an appropriate **correction** of an asymmetric deflection of a mask. (4) While the embodiments described above use the piezoelectric actuator elements, any of various other known actuators may be used for this purpose, including electrostrictive and magnetostrictive actuator elements. Further, the number of actuators may be varied if desired. (5) The features of different embodiments may be combined. For example, the technique for **correcting** the mask-deflection using the projection optical system as used in the third embodiment may be incorporated in the wafer exposure apparatus according to the first and second embodiments. (6) With the third embodiment, two detection fields in which the detection points for detecting the mask deflection lie may be defined on opposite sides of the illumination field of the light beam 100 in the scanning direction, so that the magnitude of the deflection of the mask may be detected within such one of the detection fields that is temporary in advance of the illumination field moving relative to the

mask in the scanning direction. This enables the real-time **correction** of the projected image of the mask pattern depending on the magnitude of the deflection of the mask within the illumination field of the light beam 100.

Detailed Description Text - DETX (28):
As described above, according to the embodiments of the present invention for achieving the above-mentioned first object, the deflection of a mask is detected and either the deflection of the mask is **corrected** of the projection image is **corrected** for the deflection of the mask, so that any lateral displacements of the features of the pattern and curvature of the image surface due to the deflection of the mask by the gravity, as well as any distortion and curvature of the image surface due to the thermal expansion may be reduced and thus the pattern of a mask may be advantageously performed and the projected image of the pattern of the mask shows good accuracy and stability.

Detailed Description Text - DETX (32):
The reticle R is supported by and held on a reticle holder 207 at four points by vacuum suction, for example. The reticle holder 207 is supported by a reticle stage RST through three extendable/contractible actuator elements 208. The reticle stage RST is carried on a reticle base 209 and arranged to be driven by a linear motor (not shown) for continuous linear movement in the X-direction as well as to be driven for minute **corrective** movement in the X-direction, the Y-direction and the rotational direction. There are provided two movable mirrors 211m (only one of them is shown) fixedly mounted on the top surface of the reticle holder 207 and corresponding two laser interferometer

units 211 (again, only one of them is shown) fixedly mounted on certain, stationary parts of the exposure apparatus outside the reticle holder 207. The movable mirrors 211m and the laser interferometer units 211 cooperate to measure the two-dimensional position of the reticle holder 207 (and thus of the reticle R). A main control system 214 serves to provide general control of the entire exposure apparatus. A reticle stage drive system 212 serves to control the operation of the reticle stage RST based on the measurements supplied form the laser interferometer units 211 and the control information from the main control system 214. An image formation characteristics control unit 215 serves, under the control of the main control unit 214, to control the actuation amounts of the three actuator elements 208 so as to provide fine adjustment of the height (or the position in the Z-direction) and tilt angles of the reticle R such that certain distortions (including any errors in the demagnification ratio) may be adjusted within limited adjustment ranges.

Detailed Description Text - DETX (34):

The projection optical system PL used with this embodiment is provided with an image formation characteristics **correction** mechanism. This mechanism comprises a first set of three extendable/contractible actuator elements 217 mounted on a lens barrel 216 of the projection optical system PL, a first movable lens-frame 218 holding a first lens element 219 and supported by the lens barrel 216 through the first set of actuator elements 217, a second set of extendable/contractible actuator elements 218 mounted on the first movable lens-frame 218, and a second movable lens-frame 221 holding a second lens element 222 and supported by the first movable lens-frame 218

through the second set of actuator elements 218. The main control system 214 operates the image formation characteristics control unit 215 to control the actuation amounts of the six actuator elements 217 and 220 so as to provide fine adjustment of the positions and/or tilt angles of the first and second lens elements 219 and 222 such that certain distortions (including any errors in demagnification ratio) produced by the projection optical system PL may be adjusted within limited adjustment ranges.

Detailed Description Text - DETX (44):

When the above-mentioned data representing the expected lateral displacements of the projected images on the wafer is supplied to the main control system 214, it compensates the distortion data stored in the internal-memory with the supplied data so as to generate updated distortion data which represents the distortion contributed solely by the projection optical system PL, and overwrite the internal memory with the updated distortion data. Further, each time a new reticle for actual exposure process is placed and held on the reticle stage RST, the surface shape of that reticle is measured by the surface shape detection system 230, and then the expected lateral displacements of the projected images which are expected to be produced by the measured surface shape (i.e., the expected variation in the distortion) are calculated prior to the exposure process performed using that reticle. Then, during the scanning projection exposure process, the main control system 214 calculates the expected total distortion by summing the distortion contributed solely by the projection optical system PL and the expected lateral displacements of the projected images to be caused by the

surface shape of that reticle, and controls the actuation amounts of actuator elements 208, 217 and 220 through the image formation characteristics control unit 215 so as to cancel out the expected total distortion. These actuation amounts of the actuator elements may vary during an exposure operation of one shot area depending on the current X-coordinate of the moving reticle. In this manner, the distortion contributed solely by the projection optical system PL may be evaluated with precision even when the test reticle used has a poor surface-flatness. Further, any variation in the distortion which may be caused by the surface shape of a reticle used for the exposure process can be **corrected** during the exposure process, so that the resultant projected image of the pattern transferred onto each shot area on a wafer can be free from any distortion. Accordingly, when overlay exposures are made, the overlay errors may be minimized.

Detailed Description Text - DETX (45):

Alternatively, in a case where the projection optical system PL used has been highly **corrected** for and thus free from any distortion, the image formation characteristics of the projection optical system PL may be controlled such that only the expected lateral displacements of the projected images to be caused by the surface shape of the reticle R may be eliminated. In this manner, any distortion of the transferred pattern may be minimized even when the pattern-bearing surface of the reticle R has a poor surface-flatness.

Detailed Description Text - DETX (47):

FIG. 12 shows a schematic representation of the reticle R, the projection

optical system PL and the wafer W as viewed in the scanning direction (or the X-direction) in the projection exposure apparatus of FIG. 10. As shown in FIG. 12, the reticle R held on the reticle holder 207 has a pattern-bearing surface 240 on which a pattern 242 (such as a distortion evaluation pattern) formed thereon, and the image of the pattern 242 is projected through the projection optical system PL onto the wafer W. Assuming that the projection optical system PL is free from any distortion, the image of the pattern 242 should be projected onto the wafer W at the desired position (or designed position). In such a case, the contact surfaces of the reticle holder 207 in contact with the reticle R lie in a plane perpendicular to the optical axis AX of the projection optical system PL, and will not suffer from any **deformation,** and the pattern-bearing surface of the reticle R is maintained to be completely flat.

Detailed Description Text - DETX (63):

In the above description, 1) the deflection of the reticle R by the gravity, 2) the irregularity in the pattern-bearing surface of the reticle R, and 3) the irregularities in the contact surface of the reticle holder 207 in contact with the pattern-bearing surface of the reticle R are described together with the resultant **deformation** of the pattern-bearing surface of the reticle R and lateral displacements of the features of the pattern on the pattern-bearing surface. In some cases, one of these three major factors in distortion may have much greater contribution than the other two. In other cases, two may have greater contributions than the third. In further cases, each of the three may have relatively small contributions but their contributions are cumulative so that the resultant lateral displacements of the features

of the pattern is
relatively great. Under the circumstances, it is possibly desirable to select
one or two may be selected among the three factors and be taken into
consideration for making adjustment to the projection optical system PL for
correction of the distortion which could otherwise occur.

Detailed Description Text - DETX (69):
In FIGS. 13 to 15, one-dimensional lateral displacement of the feature of
the pattern on the pattern-bearing surface of the reticle R is shown. However,
in this embodiment, the reticle R is held on the reticle holder 207 at four
points by vacuum suction. Thus, the deflection of the reticle R by the gravity
will actually cause the pattern-bearing surface to deform into a nearly
spherical surface shape, so that the feature of the pattern on the
pattern-bearing surface produces a two-dimensional lateral displacement in the
X- and Y-directions. Therefore, in order to derive the lateral displacements
of the projected images due to the **deformation** of the pattern-bearing surface
of the reticle R more accurately, it is desirable that two-dimensional lateral
displacements of the features of the pattern on the pattern-bearing surface are
derived from the surface-shape of the pattern-bearing surface and the values of
the distortion may be adjusted with respect to both the X- and Y-directions.

Detailed Description Text - DETX (78):
In a projection exposure method according to the present invention for
achieving the above-mentioned second object, the surface shape of the
pattern-bearing surface of a mask is measured and stored, and then the expected
lateral displacements of the features of the projected pattern image which are

expected to be produced by the surface shape are calculated. Then, the measurements of the distortion of the projection optical system are adjusted with the expected lateral displacements so as to derive with precision the distortion to be produced solely by the projection optical system. In the actual exposure process, an exposure is made while the positions of the features of the projected pattern image are partially **corrected** such that the distortion may be **corrected**. By virtue of this, the distortion of the projected image of the pattern may be **corrected** with great accuracy. As the result, excellent image formation characteristics may be advantageously enjoyed even if the mask has a poor flatness.

Detailed Description Text - DETX (79):

In another projection exposure method according to the present invention for achieving the above-mentioned second object, any irregularities in the contact surface of a mask and/or in the contact surface of a support member for supporting the mask are measured and stored, and then the expected surface shape of a pattern-bearing surface of the mask which is expected to occur when the mask is secured onto the support member by vacuum suction is derived from the measured irregularities. Then, the expected lateral displacements of the features of the projected pattern image which are expected to be produced by the surface shape are calculated, and the measurements of the distortion of the projection optical system are adjusted with the expected lateral displacements. Then, an exposure is made while the positions of the features of the projected pattern image are partially **corrected** such that the distortion may be **corrected**. By virtue of this, the distortion of the projected pattern image

may be **corrected** with great accuracy. As the result, excellent image formation characteristics may be advantageously enjoyed even if the mask has a poor flatness.

Detailed Description Text - DETX (84):
The reticle R is supported by and held on a reticle holder 307 at four points by vacuum suction, for example. The reticle holder 307 has a pair of parallel ribs 308A and 308B attached on the bottom surface thereof providing the reticle holder 307 with a sufficient rigidity for high speed movement. The ribs 308A and 308B are fixedly mounted on a reticle stage RST. The reticle stage RST is carried on a reticle base 309 and arranged to be driven by a linear motor (not shown) for continuous linear movement in the X-direction as well as to be driven for minute **corrective** movement in the X-direction, the Y-direction and the rotational direction. There are provided two movable mirrors 311m (only one of them is shown) fixedly mounted on the top surface of the reticle holder 307 and corresponding two laser interferometer units 311 (again, only one of them is shown) fixedly mounted on certain, stationary parts of the exposure apparatus outside the reticle holder 307. The movable mirrors 211m and the laser interferometer units 311 cooperate to measure the two-dimensional position of the reticle holder 307 (and thus of the reticle R).
A main control system 314 serves to provide general control of the entire exposure apparatus. A reticle stage drive system 312 serves to control the operation of the reticle stage RST based on the measurements supplied form the laser interferometer units 311 and the control information from the main control system 314.

Detailed Description Text - DETX (90):
The projection optical system PL used with this embodiment is provided with an image formation characteristics **correction** mechanism. This mechanism comprises a set of three extendable/contractible actuator elements 319 mounted on a lens barrel 318 of the projection optical system PL and a movable lens-frame 320 holding a lens element 321 and supported by the lens barrel 318 through the set of actuator elements 319. The main control system 314 operates an image formation characteristics control unit 315 to control the actuation amounts of the three actuator elements 319 so as to provide fine adjustment of the position and/or tilt angles of the lens element 321 such that certain distortions (including any errors in demagnification ratio) produced by the projection optical system PL may be adjusted within limited adjustment ranges. While the above arrangement drives only a single lens element, it may be preferable to modify it such that two or more lens elements of the projection optical system PL can be driven in a similar manner so as to enable adjustment or **correction** for further image formation characteristics (such as, curvature of field, comma, etc.)

Detailed Description Text - DETX (91):
It is known that the. image formation characteristics of a projection optical system PL (such as, the distortion, the position of the image plane, and others) generally vary with time in a relatively long, continuous operation of the projection exposure apparatus due to the variation in the atmospheric pressure, the variation in the ambient temperature, the heat energy buildup in the projection optical system PL received from the exposure light beam, and

other factors. In order to prevent any adverse effects of such variation of the image formation characteristics, adjustment of the image formation characteristics of the projection optical system PL is performed. For the adjustment, there are provided an atmospheric pressure sensor (not shown) for continuously sensing the atmospheric pressure and a light intensity sensor (not shown) for continuously sensing the light intensity of a partial light beam extracted from the illumination light beam IL. These sensors continuously provide detection signals, which are supplied to the main control system 314. The main control system 314 uses the detection signals to drive expected variations in the image formation characteristics, and operates the image formation characteristics control unit 315 and/or a drive mechanism for driving the material support 323 in the Z-direction (or the defocus distance **correcting** mechanism) so as to adjust the image formation characteristics of the projection optical system PL such that the expected variations in the image formation characteristics may be cancelled out. In this embodiment, the image formation characteristics control unit 315 and the material support 323 are also used to **correct** the image formation characteristics for the errors due to the **deformation** of the reticle R.

Detailed Description Text - DETX (92):

A reference mark plate 322, which is made from a glass plate having its top surface coated with an opaque film **layer,** is mounted on the material support 323 at a position adjacent to the wafer W placed on the material support 323. The top surface of the reference mark plate 322 is nominally level with the surface of the wafer W and has slits 322x and 322y extending in the Y-direction

and the X-direction, respectively, formed in the opaque film **layer** and allowing
light rays to pass therethrough. The slits 322x and 322y are used for
measuring the image formation characteristics including the distortion and the
position of the image plane.

Detailed Description Text - DETX (96):
Next, we will describe a mechanism for measuring the **deformation** of the
reticle R. In the projection exposure apparatus of FIG. 18, the reticle holder
307 has a pair of reinforcement ribs 308A and 308B for enhancing the rigidity
of the reticle holder 307 while the projection optical system PL is provided at
its upper end with the drive mechanism for a lens element, so that the space
between the bottom surface of the reticle base 309 (or of the reticle stage
RST) and the upper end of the projection optical system PL is very tight. In
view of this, in this embodiment, surface shape detection system 330 for
detecting the surface shape of the pattern-bearing surface of the reticle R
(such as, any irregularities in and tilt of the pattern-bearing surface) is
disposed below the reticle stage RST and at a position off the above-mentioned
space between the bottom surface of the reticle stage RST and the upper end of
the projection optical system PL toward the scanning direction.

Detailed Description Text - DETX (97):
In the projection exposure apparatus of this embodiment, each time a new
reticle is loaded and held onto the reticle holder 307, the pattern-bearing
surface of the reticle is measured and stored. Accordingly, it is unnecessary
to measure the surface shape of the pattern-bearing surface of the reticle
during the scanning projection exposure process as performed

using the illumination light beam IL for exposure. Rather, during the scanning projection exposure process, the stored data representing the surface shape of the pattern-bearing surface in relation with the associated X-coordinates of the reticle stage RST, is read out and used to **correct** any variation in the image formation characteristics. Because the surface shape of the reticle R may be measured an appropriate position away from the optical axis AX of the projection optical system PL, the surface shape detection system 330 need not be disposed in the above-mentioned tight space between the bottom surface of the reticle stage RST and the upper end of the projection optical system PL.

Detailed Description Text - DETX (106):

In FIG. 22, the reference member 310 has been moved in the +X-direction relative to the projection optical system PL, and the three detection light beams DLA, DLB and DLC are projected from the light sources 331A 331B and 331C, respectively, of the surface shape detection system 330 of FIG. 19 onto the reference surface (bottom surface) of the reference member 310 at the three measuring points 341A, 341B and 341C, respectively, which measuring points lie on a center line of the reference surface extending in the Y-direction at the center with respect to the X-direction. In this manner, the arithmetic operation unit 313 of FIG. 18 detects the positions in the Z-direction of the reference surface at the measuring points 341A, 341B and 341C, designated by ZA.sub.0, ZB.sub.0 and ZC.sub.0. The, as shown in FIG. 23, a part of the pattern-bearing-surface of the reticle R for the actual exposure process is moved into a position within the detection area of the surface shape detection

system 330, and the position of that portion of the pattern-bearing surface is measured. An example is described here, assuming that when the measurement of the position of the pattern-bearing surface of the reticle R is performed, the pattern-bearing surface shows a **deformation** which is uniform in the scanning direction and the reticle R is located at a starting position for the scanning projection exposure to the first of the shot areas defined on a wafer.

Detailed Description Text - DETX (109):

FIG. 21 is a schematic side elevation of the reticle R on the reticle holder 307, the projection optical system PL and the wafer W, as viewed in the +X-direction (or the scanning direction), illustrating an exemplified, possible **deformation** of the pattern-bearing surface of the reticle R. The reticle R indicated by the solid lines is completely flat with its pattern-bearing surface 340 coincident with the reference surface of the reference member (not shown), and the surface of the wafer W is coincident with the image plane of the pattern-bearing surface 340 defined by the projection optical system PL. The reticle R indicated by the imaginary lines is deformed by the gravity with its pattern-bearing surface 340A deflected thereby. The magnitudes of the deflection of the pattern-bearing surface 340A from the reference surface at the measuring points are represented by the data representing the positions in the Z-direction, .DELTA.ZA(x.sub.1), .DELTA.ZB(x.sub.1) and .DELTA.ZC(x.sub.1). The main control system 314 calculates the expected displacements of the image surface 342A defined by the projection optical system PL which are expected to occur due to the deflection of the pattern-bearing surface 340A, from the demagnification ratio .beta. of the projection optical

system PL and the data representing the positions in the Z-direction. From the result of the calculation, the field curvature of the image surface 342A and the variation .DELTA.Z in the average focus position of the image surface 342A are derived. Then, the main control system 314 operates the image formation characteristics control unit 315 of FIG. 18 to **correct** the projection optical system PL for the field curvature, by controlling the actuation amounts of the actuator elements 319. This **correction** may cause an associated variation in the average focus position. Thus, the main control system calculates the resultant variation .DELTA.Z' in the average focus position, and vary the desired value of the focus position of the surface of the wafer W (which is supplied to the wafer stage control system 326) by -.DELTA.Z'. In this manner, **corrections** are made for the field curvature and the defocus both produced by the deflection of the pattern-bearing surface of the reticle R, so that the surface of the wafer W may be brought into a position at which it will be coincident with the actual image surface of the patten-bearing surface of the reticle R with precision.

Detailed Description Text - DETX (110):

If it is expected that the **deformation** of the pattern-bearing surface of the reticle R would also affect the distortion produced by the projection optical system PL, the image formation characteristics control unit 315 is operated to make **correction** for the distortion as well. If the magnitude of the **deformation** of the pattern-bearing surface of the reticle R considerably varies depending on the position in the scanning direction, it is preferable to measure the positions in the Z-direction ZA(x.sub.i),

ZB(x.sub.i) and ZC(x.sub.i) at the three measuring points on the pattern-bearing surface of the reticle R through the surface shape detection system 330 and derive the corresponding differentials from the reference surface, each time the X-coordinate of the reticle stage RST has increased by a predetermined distance to be X.sub.i (i=2, 3, . . .) Then, the average surface of the pattern-bearing surface may be determined and the image plane of the average surface be used as the desired image plane with which the surface of the wafer W should be coincident, or alternatively, the adjustment for the field curvature as adjusted by the image formation characteristics control unit 315 and the adjustment for the desired value of the focus position as adjusted by the material support 323 may vary depending on the X-coordinate of the reticle stage RST.

Detailed Description Text - DETX (113):

Referring next to the flow chart of FIG. 24, we will describe an exemplified sequence of operations performed with the projection exposure apparatus of this embodiment for measuring the **deformation** of the pattern-bearing surface of a reticle and making an exposure while **correcting** the image formation characteristics. To begin with, at step 400 in FIG. 24, a human operator determines whether the calibration of the image formation characteristics of the projection optical system PL, or so-called lens calibration, is to be performed. The lens calibration is performed if desired in view of the stability of the image formation characteristics of the projection optical system PL. If the lens calibration is to be performed, the process proceeds to step 401, where the image formation characteristics (relating

to the distortion
and the image plane) are measured using the evaluation marks of the reference
member 310 under the control of the main control system 314 in the manner as
described above with reference to FIG. 20. Then, the process proceeds to step
402, where the main control system 314 **corrects** the image formation
characteristics such that the characteristics may be optimal with respect to
the reference surface of the reference member 310.

Detailed Description Text - DETX (116):
Then, the process proceeds to step 406, where the main control system 314
calculates the expected variation in the image formation characteristics which
is expected to occur due to the **deformation** of the pattern-bearing surface of
the reticle R as measured in comparison with the reference surface in the
manner as described above with reference to FIG. 21 and also calculates the
correction values necessary to **correct for the deformation** of the reticle R.
Since a slit-shaped exposure field is used in the scanning projection exposure,
a finer **correction** can be made by varying the **correction** values depending on
the position In the scanning direction (or the X-coordinate) of the reticle
stage RST. For example, if the reticle R suffers from some torsional
deformation, the tilt angle of the wafer W may be varied depending on the
torsional angle of the reticle R. That is, it is preferable to vary the
correction values depending on the X-coordinate of the reticle stage RST. Note
that the X-coordinate of the reticle stage RST used here is derived taking into
consideration the differential between the measuring position (or the position
in the X-direction of the measuring points of the surface shape detection

system 330) and the exposure position (or the position in the X-direction of the optical axis AX of the projection optical system PL).

Detailed Description Text - DETX (117):

Then, the process proceeds to step 407, where the exposure process for printing a circuit pattern of a semiconductor chip is commenced. For example, the wafers in a lot are sequentially loaded onto the material support 323 and the scanning projection exposure is performed to each of the shot areas defined on every wafer. Just before the commencement of the exposure process, the main control system 314 derive the total **correction** values by summing 1) the **correction** values derived at step 406 and 2) additional **correction** values for canceling out the expected variation in the image formation characteristics which is expected to occur due to variation in the atmospheric pressure and absorption of some of the illumination light energy by the projection optical system PL. Then, based on the total **correction** values, the main control system 314 drive the image formation characteristics unit 315 and the material support 323 to **correct** the image formation characteristics depending on the X-coordinates of the reticle stage RST during the scanning projection exposure to a particular shot area.

Detailed Description Text - DETX (119):

As apparent from the above, in this embodiment, the surface shape of the pattern-bearing surface of the reticle R is measured by the surface shape detection system 330 using the reference surface of the reference member 310 as the reference for the measurement, and the measurement result is used to **correct** the image formation characteristics of the exposure

apparatus.
Therefore, even when the measurements produced by the surface shape detection system 330 suffer fluctuations with time, the surface shape of the pattern-bearing surface can be measured with precision, with the result that the exposure process may be performed with the image formation characteristics maintained at a desired condition with precision.

Detailed Description Text - DETX (120):
If a reticle which has been used once or more is to be again used, and the data representing the measured surface shape of that reticle is maintained, as well as the required precision of the exposure process Is not severe, then the measurement of the surface shape of the reticle at step 405 may be bypassed to improve the throughput of the exposure process. Nevertheless, it is generally preferable not bypass the step 405 because even when the same reticle is to be used again, the position of that reticle on the reticle holder 307 may be possibly displaced from the position it occupied when previously used, because there may be a possible error in the positioning operation of the reticle loader and/or a possible foreign particle between the reticle and the reticle holder 307. Further, it is preferable to alert a human operator and stop the exposure process when a great residual error is expected even after the **correction** of the image formation characteristics or the **correction** values are insufficient, which may occur due to the presence of foreign particles or a great error in size or shape of the reticle.

Detailed Description Text - DETX (121):
In this embodiment, the surface shape of the reticle R is measured only once after the placement onto the reticle holder 307. This is

based on the assumption that the reticle R would suffer no variation in its surface shape once it is placed onto the reticle holder 307. However, if the reticle R is expected to suffer some variation in its surface shape with time and/or absorb some of the illumination light energy to thermally expand so that remeasurement would be necessitated, it is preferable to direct the process again to step 404 and/or step 405 to perform again measurement of the surface shape. In addition, while in the above description only the variation in the shape of the reticle R is considered, the orientation of the reticle R may also suffer variation since the orientation of the reticle stage RST may possibly vary depending on the position of the reticle stage RST. This is a problem relating not to individual reticles but to the projection exposure apparatus itself. Thus, in order to solve this, variations in the orientations of reticles are measured for the exposure apparatus in advance, and the **correction** values for the variations are added to the **correction** values for the surface shape of the reticle by incorporating them into the **correction** values of the image formation characteristics corresponding to the coordinates of the reticle stage. Further, if the orientation of the reticle stage RST may suffer variation depending on the velocity and/or acceleration of the reticle stage RST when moved for scanning, it is preferable to make a **correction** for such variation in the same manner as above.

Detailed Description Text - DETX (123):

Further, while in this embodiment the image formation characteristics is **corrected** by means of the drive of the lens element in the projection optical system PL and the attitude control of the material support

323 on the wafer stage WST, the image formation characteristics may be alternatively performed in other way. For example, the reticle stage RST may be provided with an attitude control mechanism, and the attitude control of the reticle may be performed by feedback control using the attitude control mechanism and the surface shape detection system 330 for providing feedback of the position of the pattern-bearing surface of the reticle. In such a case, It is preferable that the measuring points defined by the surface shape detection system 330 comprise three or more points which do not lie in a line, in order to enable determination of a plane.

Detailed Description Text - DETX (125):

In a scanning projection exposure method according to the present invention for achieving the above-mentioned third object, the surface shape of the pattern-bearing surface of a mask is measured prior to making a scanning projection exposure, and the image formation characteristics are **corrected** based on the measurement result during the scanning projection exposure, so that the sensor for measuring the surface shape of the pattern-bearing surface of the mask may be advantageously disposed with ease even when there is little space between the projection optical system and a mask stage since it may be disposed at a position away from the projection optical system to the scanning direction. As the result, by measuring the **deformation** of the mask, the expected variation in the image formation characteristics which is expected to be produced by the **deformation** may be derived and an appropriate **correction** may be made.

Detailed Description Text - DETX (127):

With a scanning projection exposure apparatus according to the present invention for achieving the above-mentioned third object, the scanning projection exposure methods described above for the third object may be conveniently performed. In the case where a reference surface is formed on a mask stage for moving the mask such that the reference surface may be substantially level with the pattern-bearing surface of the mask, and a calibration of the shape measurement system is performed using the reference surface, it is sufficient for the shape measurement system to have such stability that the measurements it provides are stable only for a very short time from when the reference surface has been measured to when the surface of the mask has been measured. Thus, even if the measurements produced from the shape measurement system tend to suffer fluctuations within a relatively short time (i.e., the shape measurement system has a poor stability), the surface shape of the mask may be measured with precision so as to make an appropriate **correction** for the variation. By virtue of this, the shape measurement system may have a relatively simple arrangement.

Detailed Description Text - DETX (133):

The uppermost of the lens elements of the projection optical system PL is a **correction** lens element 515 having a flat upper surface and a cylindrical concave lower surface as shown in cross-section in FIG. 25, which cross-section is perpendicular to the longitudinal axis (extending perpendicular to the drawing sheet surface of FIG. 25) of the reticle holder 513. Accordingly, the sectional side view of the **correction** lens element 515 along the longitudinal axis of the reticle holder 513 would show a shape of a

rectangle (or straight band). The shape of the **correction** lens element 515 is so designed as to **correct** the errors in image formation characteristics due to the deflection of the reticle R, so that the image of the pattern projected on the wafer W may be **corrected by the correction** lens element 515 with precision.

Detailed Description Text - DETX (138):

The projection exposure apparatus 500' has a unique feature that it has a projection optical system PL comprising combined **correction** lens elements 521 and 525 having no rotational symmetry about the common optical axis and associated with respective manipulation mechanisms 523 and 527. The **correction** lens elements 521 and 525 are independently rotatable about the common optical axis by means of the associated manipulation mechanisms 523 and 527, respectively. In the adjustment process, the manipulation mechanisms 523 and 527 may be operated to rotate the non-rotationally-symmetric, **correction** lens elements 521 and 525 about the common optical axis, so as to adjust the rotational positions of the lens elements 521 and 525. An example of each manipulation mechanism 523, 527 may comprise a rotary member having a plurality of holes extending in the direction of the optical axis and capable of insertion therein with an adjustment bar. When a human operator rotates the adjustment bars of the manipulation mechanisms 523 and 527 about the common optical axis so as to change the relative, optical positions of the **correction** lens elements 521 and 525, the resultant vector may be directed to any desired direction.

Detailed Description Text - DETX (140):

This exemplified adjustment process includes the determination of a reticle size (step 541), the determination of the shape and positions of the support portions of the reticle R (step 562), the calculation of the expected deflection of the reticle R (step 566) and the calculation of the expected errors produced by the expected deflection (step 564), which corresponds to the steps 561, 562, 563 and 564, respectively, shown in the design process of FIG. 26. However, the expected errors thus calculated are taken into consideration in the adjustment process for the projection lens as fixed offsets. In other words, the design of the projection lens itself is so conducted as to minimize the lens aberrations, while the desired values for adjustment process are set such that they may cancel out the expected errors to be produced by the deflection of the reticle used. The adjustment may be performed by rotating non-rotational-symmetric, **correction** lens elements as described with reference to FIG. 27, or alternatively by increasing the distance between the lens elements by a fixed offset from the design value.

Detailed Description Text - DETX (142):

In this exemplified adjustment process, the projection lens undergoes the adjustment using design values only in the fabrication process of the projection lens (step 571). Thereafter, the error components due to the deflection of the reticle are determined by, for example, making a projection exposure (step 572), and the error components are fedback to the desired values which the aberrations are to be caused to approach. The errors components due to the **deformation** of the reticle may be separated from the remaining components by, for example, acquiring the data representing the wavefront of

the projection lens with no reticle used, so as to determine the aberrations of
the projection lens itself, and then measuring the errors in the projected
pattern image which are produced when an characteristics evaluation reticle is
used, through a coordinate measurement device or the like. For evaluation of
the projected image of the reticle pattern, the errors contributed by the
projection optical system as well as the errors contributed by the original
shape of the reticle are all removed so as to derive only the error components
due to the deflection of the reticle. Then, adjustment is performed with
respect to those components to cancel out them, such that the resultant errors
are reduced zeros. This is advantageous because if adjustment were performed
using only the result of the actual printing process in the normal fabrication
of products, errors may be increased due to the difference in the deflection
between the test reticle used for the adjustment process and the reticle used
for actual printing process in the fabrication of products. After the
adjustment of the projection lens (step 574), an exposure is made again (step
542). Thereafter, if the errors are smaller than the corresponding acceptable
upper limits (YES at step 574), then the entire adjustment process is
completed.

Detailed Description Text - DETX (144):
Alternatively, in the case where the design of the projection lens is not
modified, the **correction** values for the errors may be provided as the desired
values for the adjustment, so that an exposure of a device pattern may be
performed with great accuracy as well.

Claims Text - CLTX (1):

1. A projection exposure method for exposing a substrate through a
projection optical system with a pattern formed on a mask, the mask being
supported by a predetermined support member, comprising: a first step of
calculating an amount of lateral variation of a pattern image in a direction
perpendicular to an optical axis of the projection optical system, the
variation being caused by error factors including irregularities in a contact
surface of the mask in contact with the support member and/or irregularities in
a contact surface of the support member in contact with the mask; a second
step of determining a distortion produced solely by the projection optical
system; a third step of obtaining a total expected distortion that corresponds
to a summation of the distortion produced solely by the projection optical
system and the calculated variation of the positions at which the image of the
pattern of the mask is formed; and a fourth step of exposing the substrate
while partially **correcting** the position at which the image of the pattern of
the mask is formed through the projection optical system based on the total
expected distortion.

Claims Text - CLTX (2):
2. A projection exposure method for exposing a substrate through a
projection optical system with a pattern formed on a pattern-bearing surface of
a mask, comprising: a first step of calculating an amount of lateral variation
of a pattern image, the variation being caused by irregularities in the
pattern-bearing surface of the mask; a second step of determining a distortion
produced solely by the projection optical system; a third step of obtaining a
total expected distortion by a summation of the distortion produced by the

projection optical system and the calculated variation of the pattern image;
and a fourth step of **correcting** the total expected distortion.

Claims Text - CLTX (4):

4. A projection exposure method according to claim 2, wherein the first step comprises: calculating an amount of lateral variation of the pattern image, caused by a thermal **deformation** of the mask.

Claims Text - CLTX (12):

12. A projection exposure method according to claim 2, wherein the fourth step comprises the step of scanning exposing the substrate with the pattern formed on the mask by moving the mask and the substrate in synchronization with teach other while partially **correcting** the position at which the image of the pattern of the mask is formed through the projection optical system, based on the total expected distortion.

Claims Text - CLTX (14):

14. A projection exposure method for exposing a substrate through a projection optical system with a pattern image formed on a pattern-bearing surface of a mask, comprising: a first step of determining a distortion produced solely by the projection optical system; a second step of obtaining a total expected distortion by a summation of the distortion produced solely by the projection optical system and an amount of lateral variation of the pattern image, caused by a self-weight of the mask; and a third step of exposing the substrate with the pattern image while partially **correcting** the position at which the pattern image of the mask is formed through the projection optical system based on the total expected distortion.

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